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ADVANCING REUSABLE BOOSTER SYSTEM (RBS) TECHNOLOGIES AND CAPABILITIES WITH A SPACE TOURIST SUBORBITAL VEHICLE

Barry Hellman

Integrated Systems Branch
Structures Division

Craig Remillard, Khaki McKee, and Mark Street

XCOR Aerospace

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BARRY M. HELLMAN, Project Engineer
Integrated Systems Branch
Structures Division

*//signature//

AARON M. KLOSTERMAN, Chief
Integrated Systems Branch
Structures Division

*//signature//

MARK M. DERRISO, Acting Technical Advisor
Structures Division
Air Vehicles Directorate

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Barry Hellman (Structures Division, Integrated Systems Branch (AFRL/RBSI))
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XCOR Aerospace
1314 Flight Line
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14. ABSTRACT
The Air Force is pursuing a Reusable Booster System (RBS) to meet future responsive launch needs. These needs include "within days" reconstitution, flexibility, adaptability, and assuredness. This report discusses how the aeromechanic technologies from a suborbital space tourist vehicle are being studied to further develop the aeromechanic technologies of the RBS concept.

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1. Introduction

The Air Force is pursuing a Reusable Booster System (RBS) to meet future responsive launch needs[i]. These needs include "within days" reconstitution, flexibility, adaptability, and assuredness. Future payload launch needs include 1 klbm up to 41 klbm, shown in Figure 1. A reusable booster is expected to provide at least a 50% cost reduction, 48 hour turnaround, and flexible basing. Potential architectures for a reusable booster are shown in Figure 2.

A reusable booster that is launched vertically and lands horizontally at the launch site is the current approach being pursued for these launch architectures. This type of booster is expected to be the most likely alternative pursued to provide responsive launch operations. A notional concept of operations is shown in Figure 3. At staging the booster is supersonic, significantly downrange, and flying away from its launch site. From the staging point, the booster can return to the launch site by either gliding, using its rocket engines to reverse its velocity, or carrying a secondary propulsion system (most likely a set of turbine engines) to provide the necessary energy for return.

Previous analysis has shown that in order to glide back to the launch site with delta wings, the staging Mach number must be limited to about 3[ii] assuming the vehicle is designed for a maximum subsonic L/D ratio of about 5. This approach requires an extremely large upper stage, increasing recurring costs. Staging from about Mach 5-7 optimizes the launch architecture but requires the booster to carry an additional energy source for returning to the launch site. The current baseline approach for the Air Force future plans is to carry extra propellant and use the main rocket engines on-board the booster to reverse its horizontal velocity and glide to a horizontal landing back at the launch site.[iii] This return to launch site (RTLS) concept is referred to as rocketback. By executing a rocketback RTLS trajectory instead of using a turbine engine (referred to as jetback), the vehicle becomes simpler by flying in a more benign heating environment and eliminates a major secondary subsystem (i.e. the turbine engines).[iv,v] These two main advantages of rocketback provide a simpler booster that can meet the turn-around requirement of 48 hours.

In order to help Air Force Space Command (AFSPC) and its product center the Space and Missiles Center (SMC) decide how to proceed with future launch vehicle developments, the Air Vehicle Directorate of Air Force Research Laboratory (AFRL/RB) is pursuing a reusable booster technology demonstrator.[iii] One of the critical technologies to be demonstrated is the rocketback trajectory from a simulated staging point that is representative of a likely operational staging point. These future demonstrations will bring the rocketback trajectory up to a technology readiness level (TRL) of 6, demonstration in a relevant environment.[vi] The TRL 6 definition is very similar to the technology requirements under Federal Acquisition Regulations to proceed to a Milestone B decision (i.e. an operational development program can begin)[vii]. Understanding the aeromechanics and control system requirements, and designing a rocketback flight profile that will allow booster to remain a highly operable system are critical results needed to help the Air Force make future engineering decisions about how to best develop a RBS operational system.

AFRL/RB and XCOR have established a cooperative research agreement (CRADA) that focuses on development of Lynx aeromechanics and comparison of analysis tools with flight results. This paper will present some background of the technologies that XCOR is developing and some aerodynamic trends of the Lynx.

XCOR's Lynx is a two-place manned vehicle with a double-delta wing and twin outboard vertical tails. It is designed to take off and land horizontally on a runway using its retractable/extendable tricycle landing gear. It is flown by one pilot with no computer assistance except guidance and navigation displays. The airframe is all-composite, with added thermal protection on the nose and leading edges. The wing area is sized for landing at moderate touchdown speeds. The prototype Lynx Mark I will take off from a runway under rocket power, climb to at least 62 km altitude (200,000 ft) and a maximum speed of Mach 2.2, and then reenter the atmosphere and glide to a runway landing. Lynx Mark II will have higher performance capabilities reaching 100 km altitude and Mach 3.5. In many ways this vehicle is similar to, but has significantly higher performance than, XCOR's previous rocket-powered vehicles, the EZ-Rocket and X-Racer, which have a combined total 66 flights.

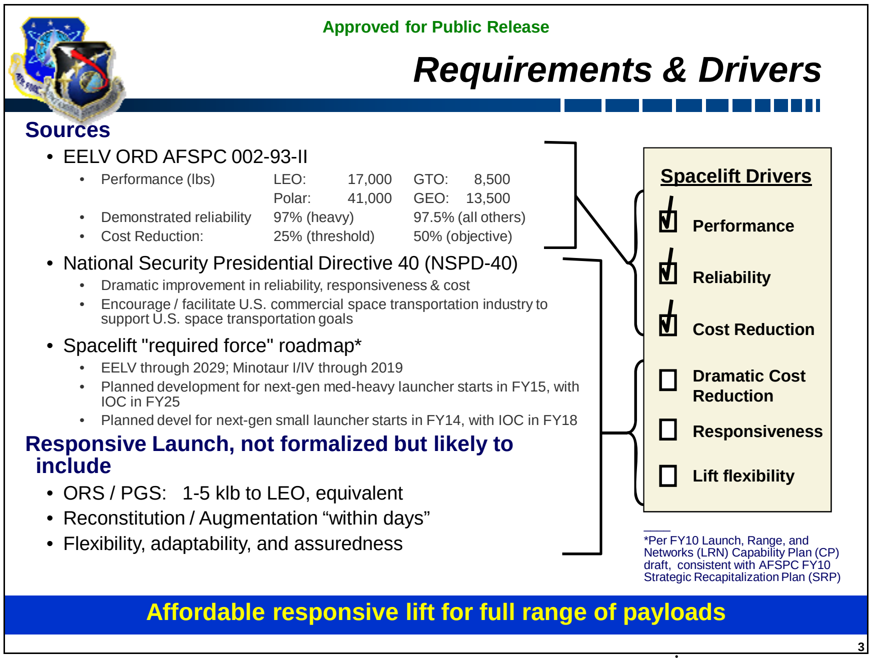

Figure 1. SDP Requirements and Drivers.[i]

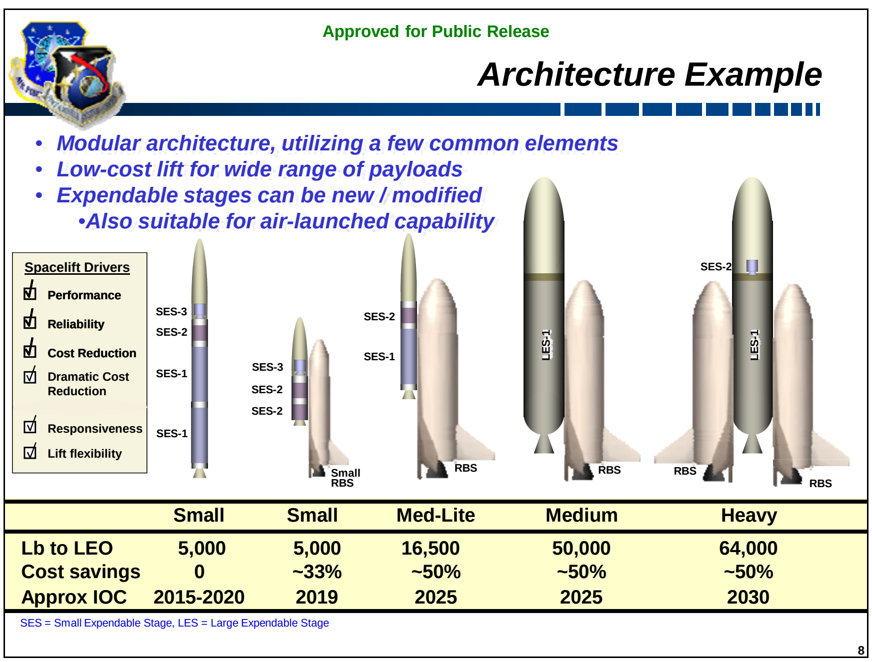

Figure 2. SDP Architecture Example that Includes Reusable Booster System.[i]

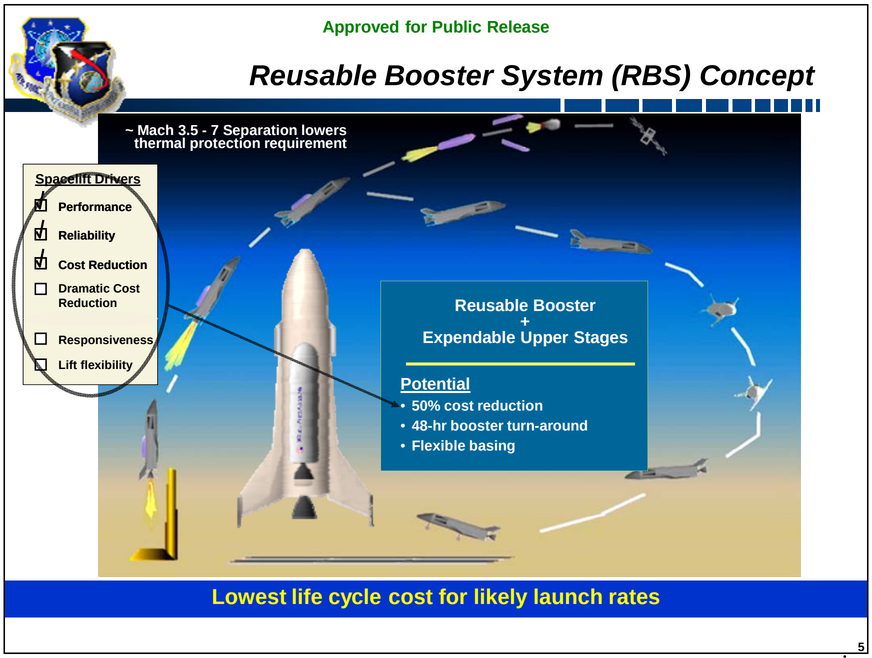

Figure 3. Notional Concept of Operations for Reusable Booster System.[i]

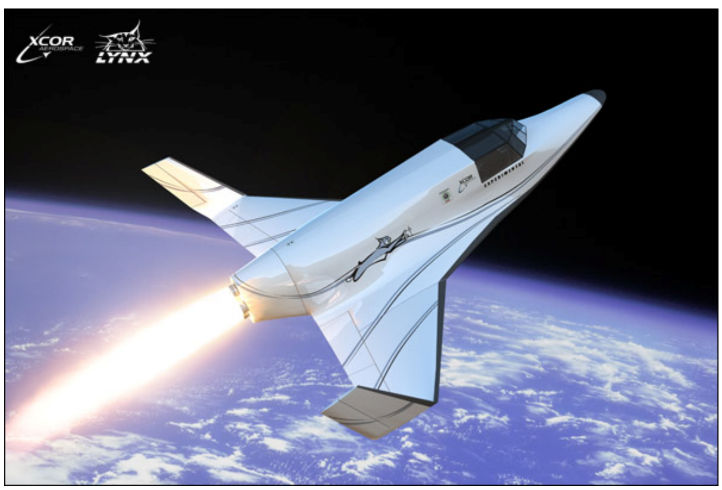

Figure 4. Artist Drawing of XCOR's Sub-Orbital Lynx Vehicle.

2. Lynx Aeromechanics

The flight profile of the Lynx, shown in Figure 5, involves a rocket-powered horizontal takeoff, suborbital exoatmospheric flight, re-entry, glide, and horizontal landing. The Lynx incorporates a double-delta wing with vertical stabilizers mounted on the wing tips. This design feature is similar to AFRL's Future responsive Access to Space Technologies' (FAST) Reference Flight System (RFS), shown in Figure 6. Since the re-entry for the Lynx flies through similar flight conditions as the re-entry from a rocketback trajectory, the data from Lynx flight tests will provide tool validation and risk reduction for a reusable booster demonstrator, which AFRL/RB is pursuing. The Lynx re-entry is compared to a rocketback from a staging point of Mach 6.5[iv] in Figure 7 through Figure 10. The Lynx will also be able to provide aeroelasticity data for using wing tip mounted vertical stabilizers.

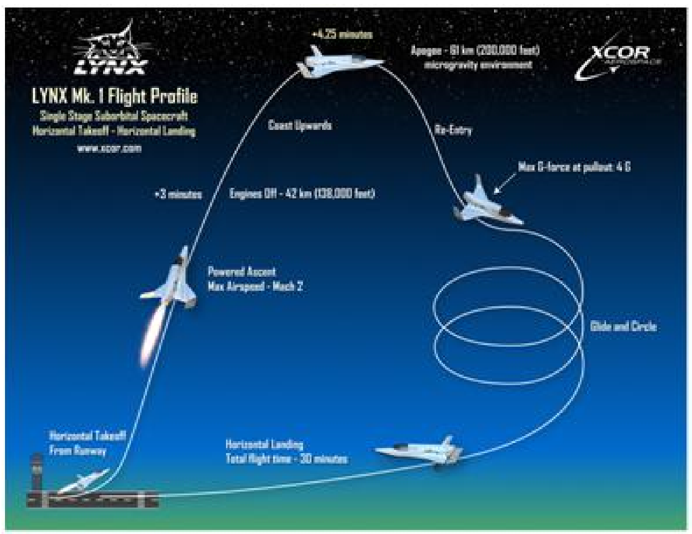

Figure 5. Flight Profile of Lynx.

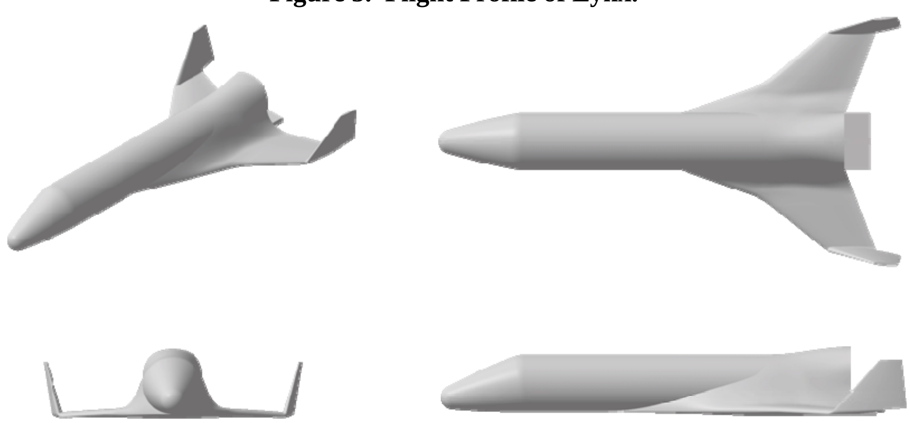

Figure 6. AFRL FAST Program Reference Flight System.

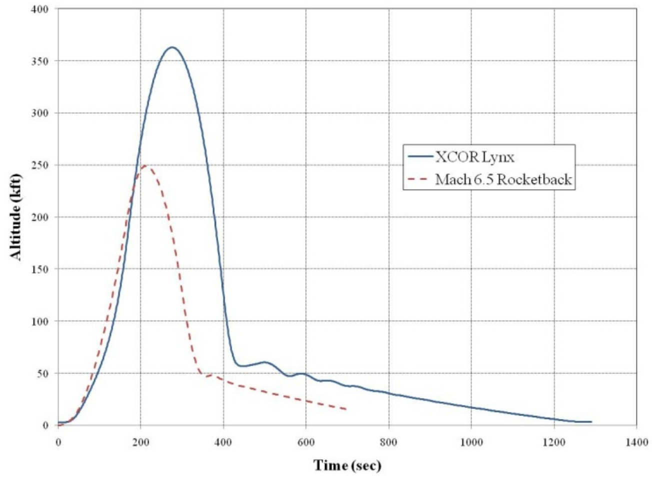

Figure 7. Altitude vs. Time Trajectory Comparison of a Reusable Booster Rocketback from Mach 6.5 Compared to the Lynx's Trajectory.

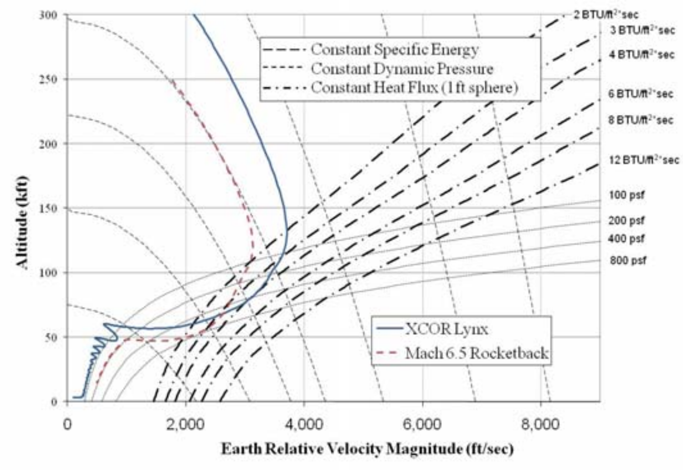

Figure 8. Altitude vs. Velocity Trajectory Comparison.

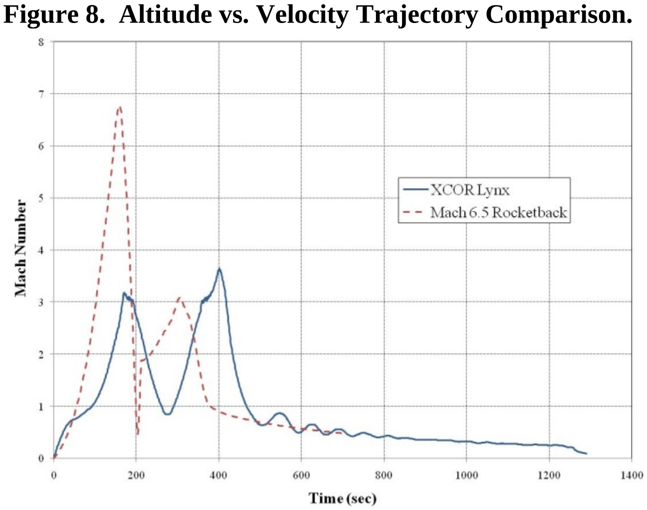

Figure 9. Mach Number vs. Time Trajectory Comparison.

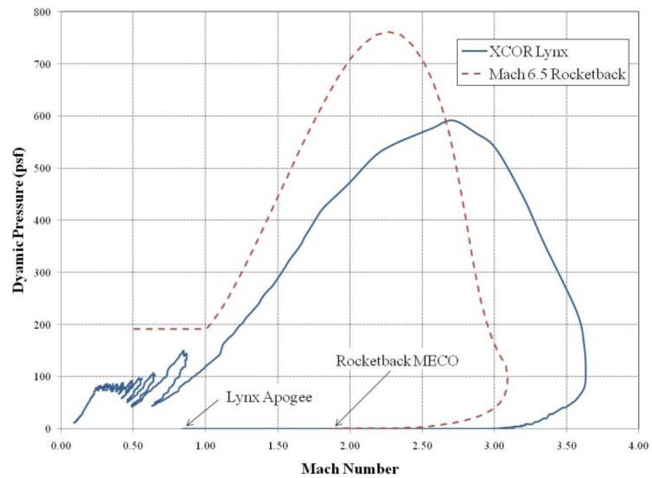

Figure 10. Dynamic Pressure vs. Mach Number Trajectory Comparison.

This design of wing tip mounted vertical fins was chosen for three main reasons over a fuselage mounted tail similar to the shuttle. First, at supersonic and hypersonic speeds, the verticals have more exposure to the freestream at angles of attack up 40 degrees, i.e. the fuselage doesn't shield vertical tails. The shuttle's vertical tail doesn't provide control authority for most of its re-entry glide. The ailerons along with the RCS system must provide the necessary yaw control. Next, using the wing tip mounted verticals reduces the amount of structural supports in the aft end of the vehicle allowing easier access to components located there which will increase the vehicle's operability. Finally, this design feature allows for easier upper stage integration on the leeward side of the vehicle, as shown in Figure 11.

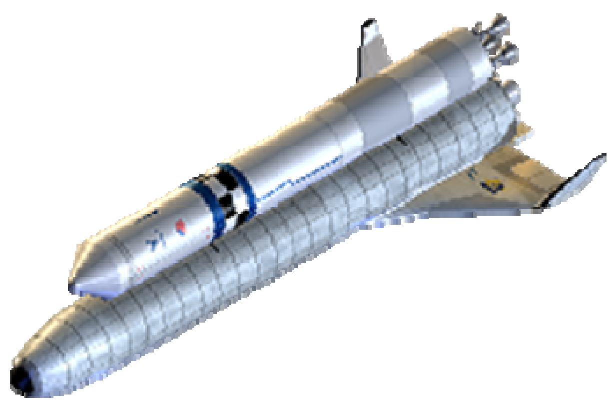

Figure 11. Example of a Potential Operational Reusable Booster with an Upper Stage Integrated on the Leeward Side[viii].

This design idea was studied at NASA Langley as an upgrade for the Space Shuttle, shown in Figure 12. This configuration would deflect each rudder outward for control and to serve as a speed brake. This effort involving tunnel testing and control system analysis showed that the tip-fin controllers could adequately control the orbiter during entry, reduce drag during the terminal area approach, and be able to handle the landing gust requirements of the shuttle. However, use as a speed brake would be reduced by about 65%.

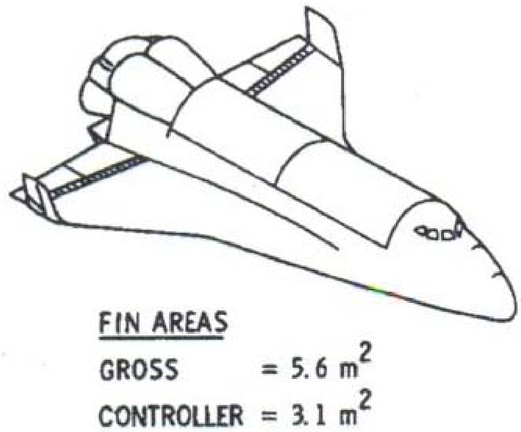

Figure 12. Potential Space Shuttle Modification with Wing Tip Vertical Stabilizers[ix].

The Lynx geometry has been analyzed using NASA Ames' Euler CFD Solver called CART3D.[x] Yaw static stability analysis from Mach 0.7 up to Mach 3 at 30º angle of attack is shown in Figure 13. This chart shows that the change in wind axis yawing moment with sideslip angle is positive indicating static stability.

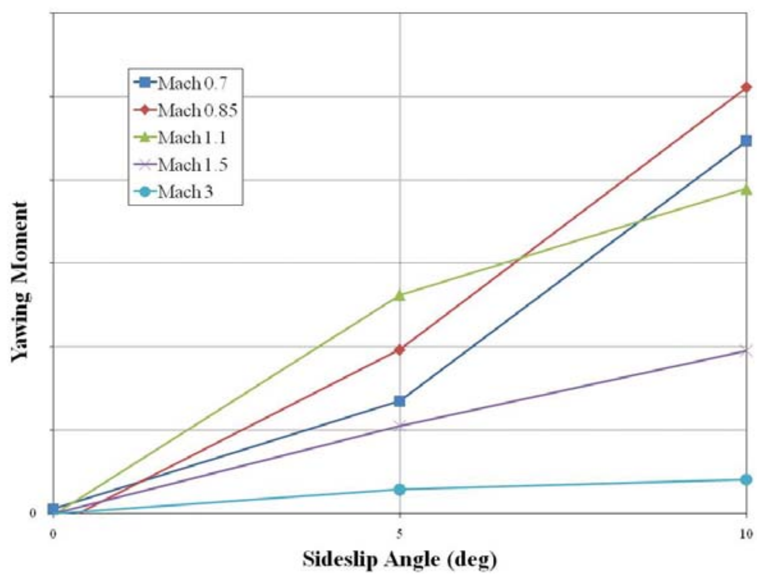

Figure 13. Yaw Moment vs. Sideslip Angle for Lynx Analyzed with CART3D.
(Note: Yaw Moment Axis Values Removed due to data being proprietary)

In March of 2009, XCOR tested a model of the Lynx at the Vertical Wind Tunnel at Wright Patterson AFB.[xi] This test was used to begin validating various CFD models and to look at the aerodynamics and stability of the vehicle during low speed phases of flight. A diagram of the tunnel is shown in Figure 14. The Lynx was tested at the tunnel's maximum speed of about Mach 0.13. The resulting yaw moment data from this test is shown in Figure 15. At the higher angles of attack, the wing tip vertical stabilizers are keeping the vehicle stable. However, this test showed some yaw stability issues flying in a strong crosswind at 0º angle of attack since the curve begins to have a negative slope.

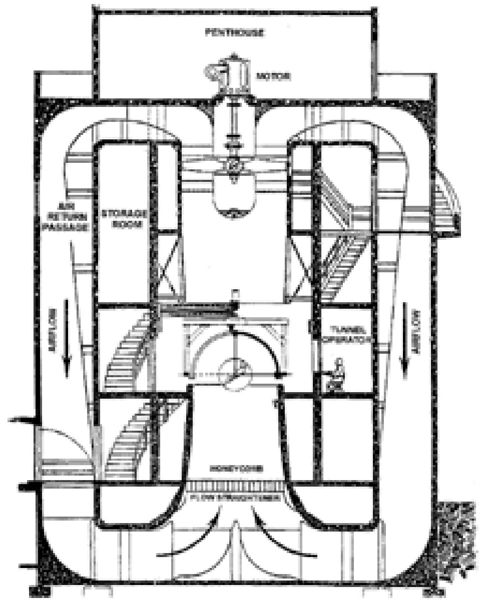

Figure 14. Diagram of Wright-Patterson Vertical Wind Tunnel[xii].

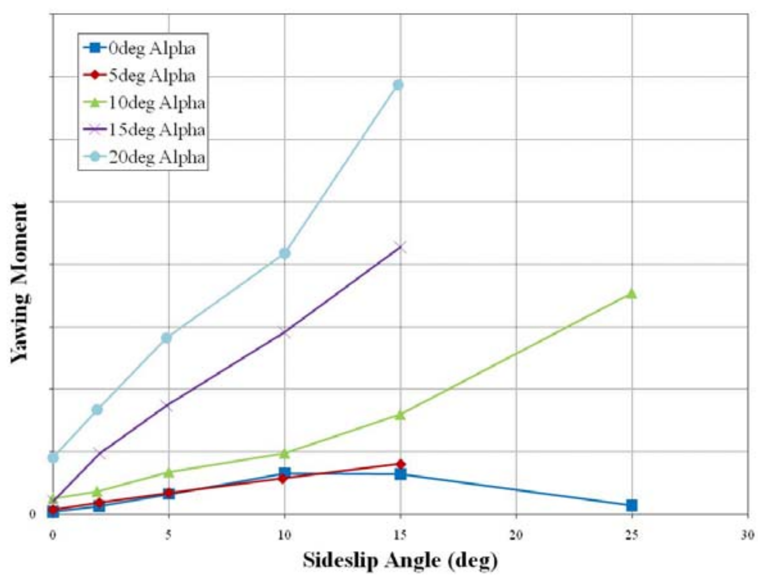

Figure 15. Incompressible Yaw Moment Data of the Lynx from the Vertical Wind Tunnel at Wright-Patterson AFB.

List of Acronyms, Abbreviations, and Symbols

Acronym/ Abbreviation	**Description**
CRADA	Cooperative Research and Development Agreement
CFD	Computational Fluid Dynamics
FAST	Future responsive Access to Space Technologies
RBS	Reusable Booster System
RFS	Reference Flight System
SDP	Spacelift Development Plan
TRL	Technology Readiness Level

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